Evidence for Terrestrial Planetary System Remnants at White Dwarfs

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Abstract.
The last several years have brought about a dynamic shift in the view of exoplanetary systems in the post-main sequence, perhaps epitomized by the evidence for surviving rocky planetary bodies at white dwarfs. Coinciding with the launch of the *Spitzer Space Telescope*, both space- and ground-based data have supported a picture whereby asteroid analogs persist at a significant fraction of cool white dwarfs, and are prone to tidal disruption when passing close to the compact stellar remnant. The ensuing debris can produce a detectable infrared excess, and the material gradually falls onto the star, polluting the atmosphere with heavy elements that can be used to determine the bulk composition of the destroyed planetary body.

Based on the observations to date, the parent bodies inferred at white dwarfs are best described as asteroids, and have a distinctly rocky composition similar to material found in the inner Solar System. Their minimum masses are typical of large asteroids, and can approach or exceed the mass of Vesta and Ceres, the two largest asteroids in the Solar System. From the number of stars surveyed in various studies, the fraction of white dwarfs that host terrestrial planetary system remnants is at least a few percent, but likely to be in the range $20-30\%$. Therefore, A- and F-type stars form terrestrial planets efficiently, with a frequency at least as high as the remnants detected at their white dwarf descendants.

Keywords: circumstellar matter— minor planets, asteroids— planetary systems – stars: abundances— stars: evolution— white dwarfs
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INTRODUCTION AND BACKGROUND

White dwarfs are the end state for over 95% of all stars in the Galaxy, including our Sun, and their circumstellar environments represent the ultimate fate for essentially all planetary systems as well as the Solar System. Only low-mass stars of spectral type K and M are more common than white dwarfs both in the Solar neighborhood[1] as well as the Galaxy at large. The disk white dwarfs seen today are primarily the descendants of A- and F-type stars with masses $1.2-3.0\,M_{\odot}$, although their population contains the remnants of all intermediate-mass stars that avoid core collapse.

Hence white dwarf are *evolved but not necessarily old*. The nearest white dwarf to the Sun is Sirius B with a total age near 250 Myr (Liebert et al. 2005), while the Pleiades, Hyades, and Praesepe young open clusters together contain more than one dozen white dwarf members. The low and typically blue-peaked luminosities of white

[1] `http://www.recons.org`

dwarfs make them excellent targets for direct imaging planet searches and substellar companion studies in general.

White Dwarfs as Heavy Element Detectors

Surface gravities of $\log g\,[(\mathrm{cm\,s^{-2}})] = 8$, assisted by the onset of convection, ensure that heavy elements sink rapidly in the atmospheres of white dwarfs as they cool below 25 000 K (Koester 2009; Paquette et al. 1986). From this point forward in evolution, the timescales for metals to diffuse below the photosphere are always a few to several orders of magnitude shorter than the cooling age. Thus, cool white dwarfs should have atmospheres composed of pure hydrogen or helium, an expectation corroborated by observation (Eisenstein et al. 2006).

Interestingly, a significant fraction of these stars display photospheric absorption lines due to metals when viewed with high-powered optical spectroscopy (Koester et al. 2005; Zuckerman et al. 2003). These atmospheric heavy elements are external pollutants that imply ongoing accretion rates above $10^{8}\,\mathrm{g\,s^{-1}}$ or metal masses on the order 10^{22} g within the convection zone of the star (Farihi et al. 2010a; Koester & Wilken 2006). While mass can be accreted via Roche lobe overflow or stellar wind of a binary companion, for *single* white dwarfs with metals the two possibilities are the interstellar medium or circumstellar material. Regardless of the source of photospheric contamination, *the heavy element abundances in cool white dwarfs indirectly measure the composition of the accreted matter*.

Two Important Polluted Prototypes

van Maanen 2

Figure 1 shows the optical spectrum of the prototype metal-polluted white dwarf and nearest single degenerate star to the Sun, vMa 2. The prominent calcium and iron absorption features led (van Maanen 1917) to initially conclude his high proper motion star was of early F-type. Only 40 years later was it understood that these remarkably strong features in a white dwarf were due to a metal abundance 30 000 times lower than solar (Weidemann 1960). Thus, white dwarfs can be detectably polluted by a relatively small amount of metals. The calcium K line is the trademark of metal-polluted white dwarfs, as this feature is detected in the optical spectra of all members of this class.

vMa 2 is a helium atmosphere white dwarf with metals. Such stars have spectral type DBZ or DZ (D for degenerate star; B if warm enough to exhibit helium lines; Z for metallic features). Owing to the relative transparency of helium, the first two dozen externally polluted white dwarfs discovered were of this same spectral class; hydrogen-poor stars enriched by metals (Sion et al. 1990). Their hydrogen deficiency was the first and still most fundamental problem with the interstellar accretion hypothesis. Because hydrogen floats and heavy elements sink, the abundance pattern in DBZ stars is precisely the opposite of expectations if hydrogen-dominated interstellar matter were the source

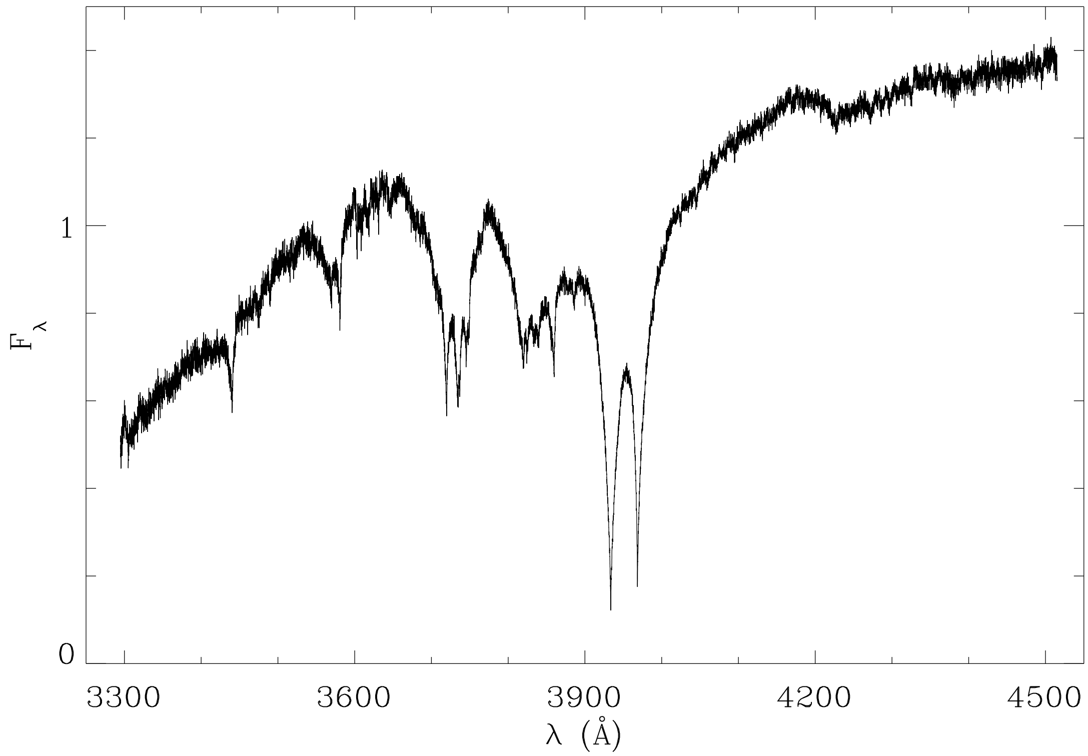

FIGURE 1. vMa 2 was the third white dwarf to be discovered (van Maanen 1919), and is the prototype of the DZ spectral class. This $R \approx 20\,000$ VLT UVES spectrum (which extends to 6700Å) reveals only metallic lines of iron, calcium, and magnesium; the pollution is refractory-rich yet hydrogen deficient. From the SPY project (Napiwotzki et al. 2003).

of the atmospheric pollution.

G29-38

Figure 2 displays the optical spectrum of the metal-rich white dwarf G29-38 (Koester et al. 1997). The relatively weak calcium K line in this star implies a metal abundance 1500 times higher than in vMa 2, because G29-38 has a hydrogen atmosphere and corresponding spectral type DAZ (D for degenerate star; A for hydrogen lines; Z for metallic features). Its ultraviolet spectrum exhibits numerous iron features and magnesium (Koester et al. 1997), the latter is also seen in a high-resolution optical spectrum (Zuckerman et al. 2003),

Although not the prototype of its spectral class, the importance of G29-38 rests upon the detection of $T \approx 1000\,$K circumstellar dust (Zuckerman & Becklin 1987) ten years prior to the photospheric metals. Together, these observational data indicate the dust orbits sufficiently close to pollute the star via infall, and corroborates dust temperature

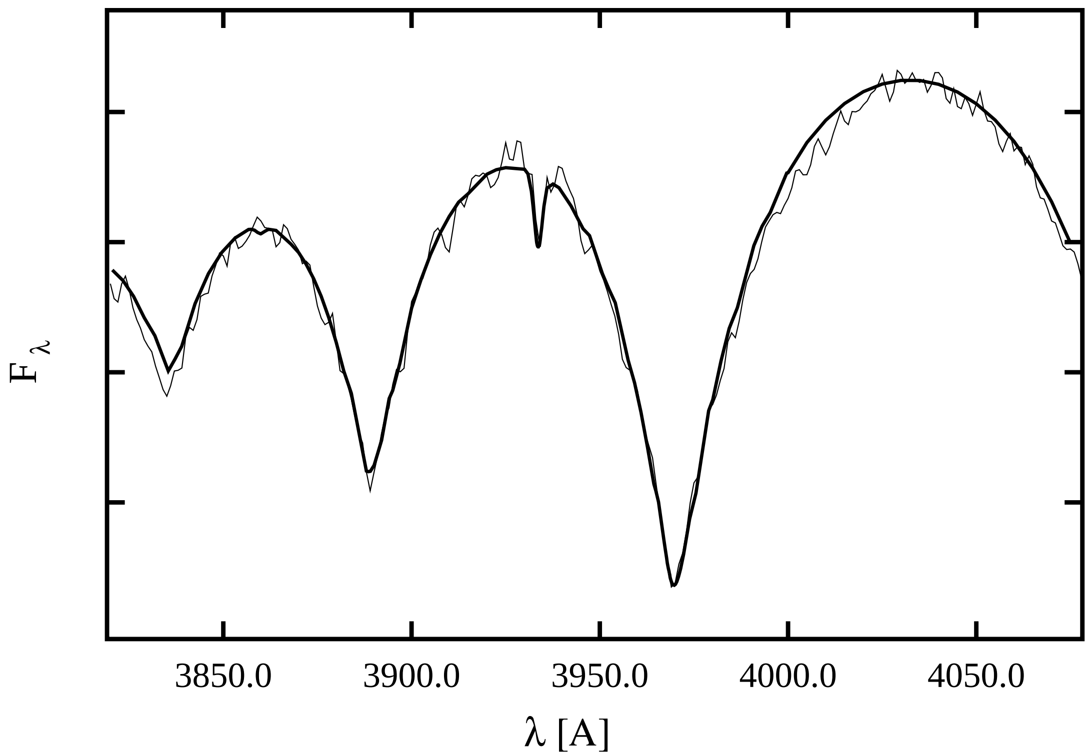

FIGURE 2. The detection of the Ca II K-line in the optical spectrum of G29-38. Note the much stronger line seen in vMa 2 represents an abundance 1500 times lower than determined for G29-38. Line strength is a strong function of atmospheric composition (i.e. hydrogen or helium) and stellar effective temperature. From Koester et al. (1997).

inferred from the observed infrared excess. G29-38 is the prototype dusty white dwarf, and the only known instance of circumstellar dust and photospheric metals prior to the launch of *Spitzer*.

Metal-Contaminated White Dwarfs at Large

Understanding externally polluted white dwarfs themselves is key to the nature of the source of their contamination. The helium-rich DBZ stars have been observed in significant numbers for many decades, though mainly as a result of their atmospheric transparency. Metals may persist in DBZ stars at detectable levels for 10^6 yr timescales (Paquette et al. 1986), and combined with their $10^8 - 10^9$ yr cooling ages, it is understandable the interstellar medium was initially the prime culprit for their pollution (Dupuis et al. 1993a,b, 1992). In addition to the problem of their hydrogen deficiency, there remained insufficient evidence for local interstellar clouds responsible for many nearby polluted stars (Aannestad et al. 1993).

The gradual discovery of numerous members of the DAZ spectral class (Zuckerman & Reid 1998; Holberg et al. 1997; Lacombe et al. 1983) provided new insights into the general issue of white dwarf pollution. The heavy element sinking timescales in

hydrogen atmosphere white dwarfs can be a short as *a few days* (Paquette et al. 1986), implying the observed abundances in DAZ stars are maintained by *ongoing metal accretion*. Inferred metal accretion rates for these stars are typically on the order of 10^8 g s^{-1} but again the necessary, local interstellar clouds are distinctly lacking (Koester & Wilken 2006; Zuckerman et al. 2003).

The two major differences between the DAZ and DBZ stars is the size of the convection zone and the transparency of their atmospheres. The former leads to the sizable difference in the metal diffusion timescales (Koester 2009) and the latter determines the detectability of metals for a given abundance. To summarize:

- DAZ white dwarfs have *hydrogen* atmospheres, *thin* convection zones, *short* diffusion timescales and hence accretion of heavy elements is inferred to be ongoing.
- DBZ white dwarfs have *helium* atmospheres, *long* diffusion timescales, *deep* convection zones and thus contain large masses of heavy elements in their outer layers.

Combined with the difficulties with the interstellar accretion hypothesis, these two properties – the large masses of metals already accreted by DBZ stars, and the ongoing metal accretion by the DAZ stars – led to the generation of ground- and space-based programs to detect and study circumstellar dust at metal-polluted white dwarfs.

DUST DISK SEARCHES AND STUDIES

While the detection of dust at G29-38 took place 17 years prior to the launch of *Spitzer*, it was during this latter era that a wealth of data and insight were achieved in the study of metal-contaminated white dwarfs and their circumstellar environments. The increased attention and research focussed on white dwarfs and circumstellar dust began soon after Zuckerman et al. (2003) published the first extensive and successful survey to detect nearby DAZ stars and Jura (2003) published the tidally disrupted asteroid model for G29-38.

Destroyed Minor Planets in the Post-Main Sequence

Two influential models emerged between 2002 and 2003 that lent theoretical support to the idea of circumstellar pollution in cool white dwarfs. The first was a model of planetary system instabilities introduced by post-main sequence mass loss. Debes & Sigurdsson (2002) demonstrated that following the bulk of mass loss during the asymptotic giant brach, the unperturbed semimajor axis ratios in multiple planet systems are unchanged, but new resonances are established. In essence, the planetary system becomes dynamically young again for a timescale of 10^8 yr, similar to proto-planetary systems and that inferred for the Solar System.

Jura (2003) utilized this general picture of a dynamically renewed planetary system to account for all the observed properties of G29-38 by modeling its dust disk as the result of a tidally destroyed asteroid. In this picture, a previously stable asteroid is perturbed into a high eccentricity orbit that passes within the Roche limit of the white dwarf, where it is shredded by gravitational tides. Via collisions, the debris rapidly produces

TABLE 1. The First 18 White Dwarfs with Infrared Excess Due to Circumstellar Dust

WD	Name	Type	T_{eff} (K)	Year	Telescope	Reference*
2326+049	G29-38	DAZ	11700	1987	IRTF	(1)
1729+371	GD 362	DBZ	10500	2005	IRTF/Gemini	(2,3)
0408−041	GD 56	DAZ	14400	2006	IRTF	(4)
1150−153	EC 11507−1519	DAZ	12800	2007	IRTF	(5)
2115−560	LTT 8452	DAZ	9700	2007	*Spitzer*	(6)
0300−013	GD 40	DBZ	15200	2007	*Spitzer*	(7)
1015+161	PG	DAZ	19300	2007	*Spitzer*	(7)
1116+026	GD 133	DAZ	12200	2007	*Spitzer*	(7)
1455+298	G166-58	DAZ	7400	2008	*Spitzer*	(8)
0146+187	GD 16	DBZ	11500	2009	*Spitzer*	(9)
1457−086	PG	DAZ	20400	2009	*Spitzer*	(9)
1226+109	SDSS 1228	DAZ	22200	2009	*Spitzer*	(10)
0106−328	HE 0106−3253	DAZ	15700	2010	*Spitzer*	(11)
0307+077	HS 0307+0746	DAZ	10200	2010	*Spitzer*	(11)
0842+231	Ton 345	DBZ	18600	2008	*AKARI*	(11)
1225−079:	PG	DBZ	10500	2010	*Spitzer*	(11)
2221−165	HE 2221−1630	DAZ	10100	2010	*Spitzer*	(11)
1041+091	SDSS 1043	DAZ	18300	2010	CFHT/Gemini	(12)

* (1) Zuckerman & Becklin 1987; (2) Becklin et al. 2005; (3) Kilic et al. 2005; (4) Kilic et al. 2006; (6) Kilic & Redfield 2007; (6) von Hippel et al. 2007; (7) Jura et al. 2007a; (8) Farihi et al. 2008b; (9) Farihi et al. 2009; (10) Brinkworth et al. 2009; (11) Farihi et al. 2010c; (12) Melis et al. 2010

small dust particles orbiting in a vertically optically thick, geometrically thin (flat) disk. The closely orbiting dust 1) emits in the infrared, producing the observed excess at G29-38, and 2) gradually falls onto the star, polluting its atmosphere with the observed heavy elements. This is currently the standard model for metal-enriched white dwarfs with infrared excess.

First *Spitzer* Observations of White Dwarfs with Dust and Metals

The first two white dwarfs found to have circumstellar dust disks were naturally premier targets for *Spitzer*. Figure 3 shows the full spectral energy distributions (SEDs), including infrared data obtained by *Spitzer* for G29-38 and the second white dwarf found to have circumstellar dust, GD 362 (Becklin et al. 2005; Kilic et al. 2005). It is noteworthy that the strength and shape of their thermal continua are similar, with a very warm temperature excess and no cool component.

Both stars have strong emission features due to silicate dust particles, specifically olivines similar to in their emission to solids found in the zodiacal cloud and orbiting stars like β Pic where planet formation is ongoing (Jura et al. 2007b; Reach et al. 2005). Compared to G29-38, the infrared emission from GD 362 is spectacular and perhaps the strongest silicate emission ever seen at a mature star (Song et al. 2005). The remarkable infrared properties of GD 362 are matched by its highly polluted atmosphere (Zuckerman et al. 2007; discussed below).

Importantly, the infrared emission of both stars is well-modeled by the optically thick,

flat disk models of Jura (2003), placing all the circumstellar material within $1\,R_\odot$ of the white dwarf. At this distance, any rocky parent body larger than a few km in size would become tidally disrupted (Davidsson 1999), making the observations consistent with a destroyed minor planet.

Disk Properties: Infrared Photometry and Spectroscopy

As of this writing (mid-2010), there are 18 metal-contaminated white dwarfs known to have an infrared excess owing to circumstellar dust as confirmed via *Spitzer* mid-infrared observations (Farihi et al. 2010c, 2009; Brinkworth et al. 2009; Farihi et al. 2008b; von Hippel et al. 2007; Jura et al. 2007a,b; Reach et al. 2005). Table 1 lists these white dwarfs with dust disks in order of the discovery by publication date, together with the stellar effective temperature, spectral type, and the telescope that first detected the excess emission. As can be seen from the Table, *Spitzer* has been instrumental in this field.

More than 60 metal-rich white dwarfs have been observed with *Spitzer* IRAC at wavelengths between 3 and 8 μm, and roughly half were observed with MIPS at 24 μm before the end of the cryogenic lifetime (Farihi et al. 2009). Eight white dwarfs with disks were observed spectroscopically with *Spitzer* IRS between 5 and 15 μm (representing all observable white dwarfs with disks at the time). From this large dataset, it is found that all dust disks detected at white dwarfs share a common set of characteristics, supporting the idea that a single mechanism is responsible for their appearance.

1. Circumstellar dust at white dwarfs is well-modeled by geometrically thin, flat disks that are vertically optically thick at wavelengths as long as 20 μm.
2. Infrared emission from dust at white dwarfs is very warm, with the inner disk at temperatures ($T \sim 1200\,$K) where grains rapidly sublimate.
3. The outer disk radius is always constrained to lie within the tidal breakup limit for km-size or larger bodies; there is no evidence for cool dust at white dwarfs.
4. *Minimum* dust masses are 10^{18} g, but because the disks are optically thick (and based on additional evidence) the disks may have masses as large as 10^{24} g.
5. Infrared spectroscopy reveals the orbiting material is rich in silicate minerals (olivine primarily but also possibly pyroxene), and deficient in carbon and hydrogen.
6. The stellar pollution caused by the infall of disk material is rich in refractory and transitional metals, but poor in volatile elements.

The observed properties provide a few important constraints on the origin and behavior of the circumstellar material. First, the lack of cool dust at white dwarfs implies the material has not been captured from the interstellar medium. Such material would migrate inward from the Bondi-Hoyle radius (roughly 1 AU for a typical white dwarf), but the compact nature of these disks ($r < 0.01$ AU) rules out material at these distances (Farihi et al. 2009; Jura et al. 2007a). Second, the material is depleted in volatile elements, such as carbon, relative to metals and similar to matter found within the inner Solar System (Jura et al. 2009a; Farihi et al. 2008b; Jura 2006; Reach et al. 2005; Lod-

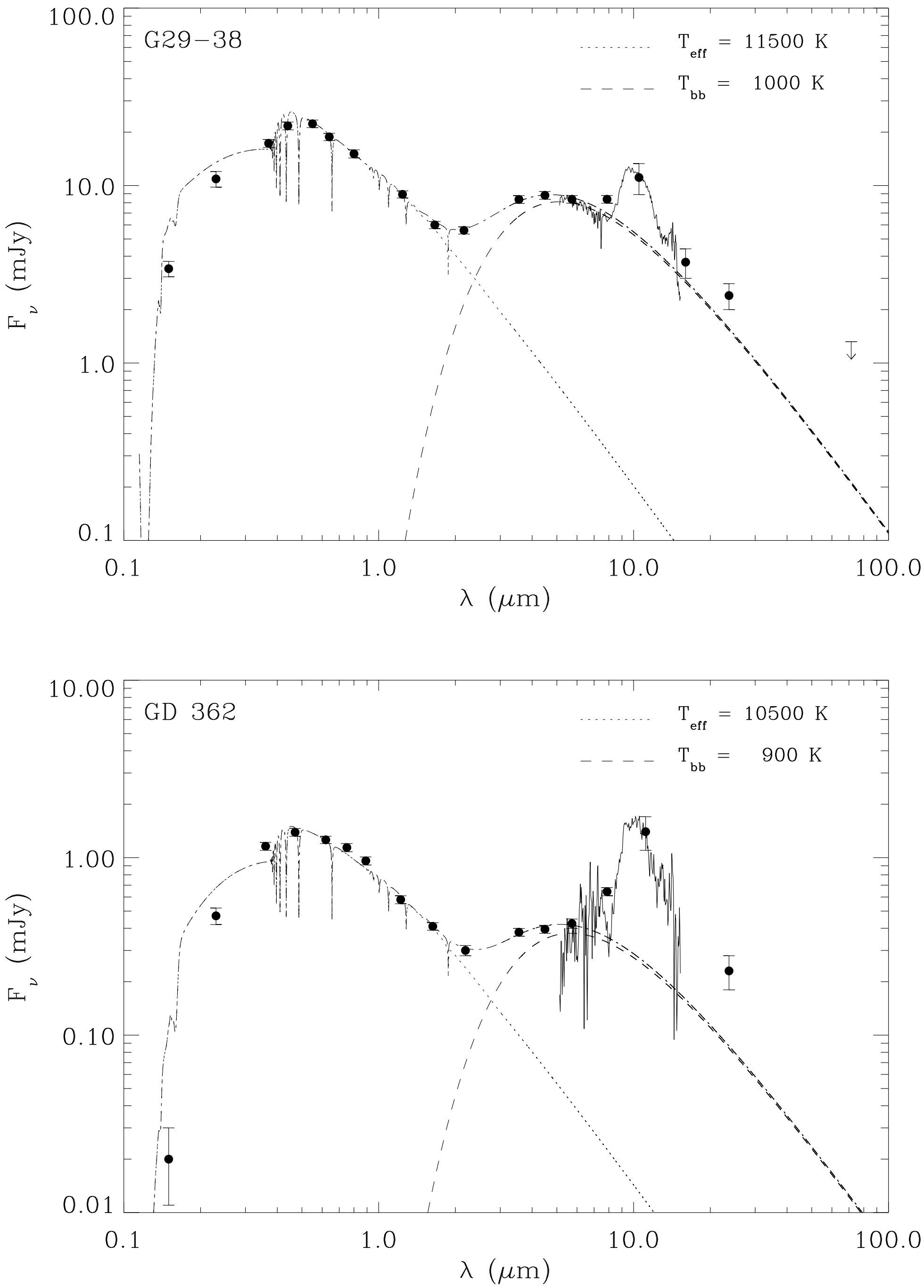

FIGURE 3. The broad SEDs of G29-38 and GD 362. The data points with error bars show short wavelength and *Spitzer* photometry fitted by 1) stellar atmosphere models drawn as dotted lines, and 2) thermal blackbody models shown as dashed lines. Also shown are their *Spitzer* infrared spectra revealing strong silicate emission from olivine particles (Jura et al. 2007b; Reach et al. 2005).

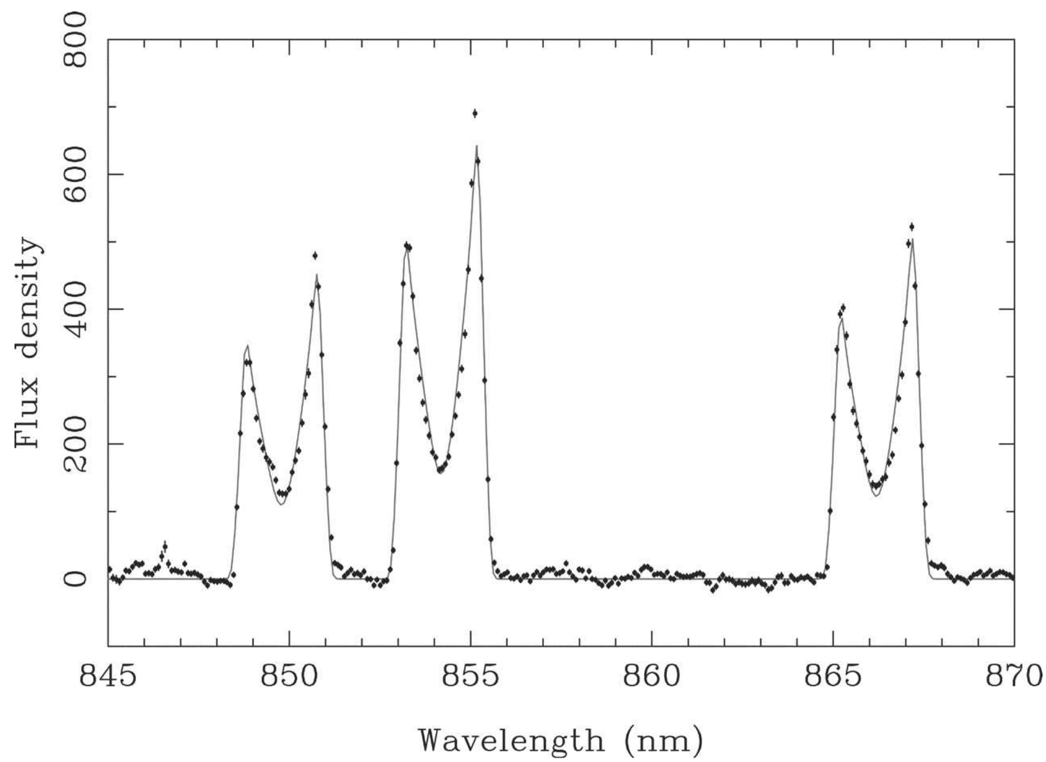

FIGURE 4. Calcium emission in the optical spectrum of SDSS 1228. The width of the emission lines indicates Keplerian rotation at $\pm$ 630 km s^{-1}. Emission lines from iron are also seen in this star, but not from hydrogen or helium. From Gänsicke et al. (2006).

ders 2003). Third, the dust disks persist all the way up to temperatures where dust should rapidly sublimate, precisely as expected for material that is delivering heavy elements to the photosphere of its white dwarf.

In summary, *the debris orbiting white dwarfs is rocky. The gradual pollution of the stellar atmosphere by the circumstellar material provides a powerful tool to measure the bulk chemical composition of extrasolar, rocky planetary bodies such as asteroids, moons, and potentially major planets*.

Disks with Metallic Gas Components

There are three white dwarfs with dust and photospheric metals that were initially discovered due to the presence of metallic, *gaseous* emission lines in the optical (Gänsicke et al. 2008, 2007, 2006). Found serendipitously in the Sloan Digital Sky Survey (SDSS), each of these white dwarfs shows optically thick emission lines in the calcium triplet in the far-red region of their optical spectra. Furthermore, these emission lines are precisely the type that are seen in the gas-dominated accretion disks of cataclysmic variables, but in these *single* white dwarfs with disks, hydrogen and helium are seen only in absorption (Gänsicke et al. 2008). Therefore, the emitting material is solely composed of heavy elements.

Importantly, the gaseous, emitting disk components yield empirical constraints on their radial location, placing them firmly within about $1.2\,R_{\odot}$. This comes directly from Kepler's laws applied to the observed velocity broadening of the emission features (Gänsicke et al. 2006). While the modeling of the dust emission in the infrared indicates similar radial distributions for disks at white dwarfs, these stars with metallic emission corroborate and strengthen the idea that disks at cool white dwarfs result from the tidal destruction of asteroids.

The gaseous debris in these systems coexists with dust, and is part of the same phenomenon as the dusty white dwarfs where calcium emission lines are not seen (Melis et al. 2010). That is, the gas is not the result of sublimated dust very close to the white dwarfs, as the dust and gas occupy the same circumstellar regions (Brinkworth et al. 2009). Rather, the gas is the result of energetic collisions within a rapidly rotating disk with speeds exceeding $0.001c$ – if the velocity dispersion among dust particles is only 1%, then collisions at $6\,\mathrm{km\,s^{-1}}$ will occur and grind solids into gas (Jura 2008).

Disk Properties: Stellar Spectroscopy

Because cool white dwarfs should have pure hydrogen or helium atmospheres, spectroscopy of the metal-contaminated stars indirectly yields the elemental abundances in the accreted material. Jura (2006) showed that several metal-lined white dwarfs have iron-to-carbon ratios that are super solar, indicating the material originated in a high temperature region of its host system (i.e. the inner system). Furthermore, the two published cases where detailed abundance analyses were obtained high-powered spectroscopy reveal material broadly similar to the terrestrial planets (Klein et al. 2010; Zuckerman et al. 2007).

Not only are the compositions of metal-enriched white dwarfs distinctly rocky and indicative of asteroidal or terrestrial debris, but so are the metal masses. In helium-rich DBZ stars such as GD 362 and GD 40, the total mass of heavy elements in the mixing layer of the stars is greater than 10^{22} g; more material than contained in a typical 200 km Solar System asteroid(!). However, this is only the mass of metals currently within the outer layers, and hence the *minimum* mass of the accreted matter. If the star has possessed a disk for a few to several diffusion timescales (rather likely in the case of GD 40 Klein et al. 2010), then the total mass of heavy elements involved is approaches the masses of Vesta and Ceres, the two largest asteroids in the Solar System. In the case of GD 362, in order to account for all of its spectacular properties with a single pollution event, Jura et al. (2009b) find that the necessary parent body mass is between that of Jupiter's moon Callisto and Mars, including *evidence for water*.

A PICTURE OF PLANETARY SYSTEM REMNANTS

The *Spitzer* and ground-based detections of circumstellar dust are useful in that they support an emerging picture of rocky planetary system remnants, and provide a physical and chemical link between the orbiting debris and the photospheric heavy elements. In this manner, astronomers now have a powerful tool to study the composition of extra-

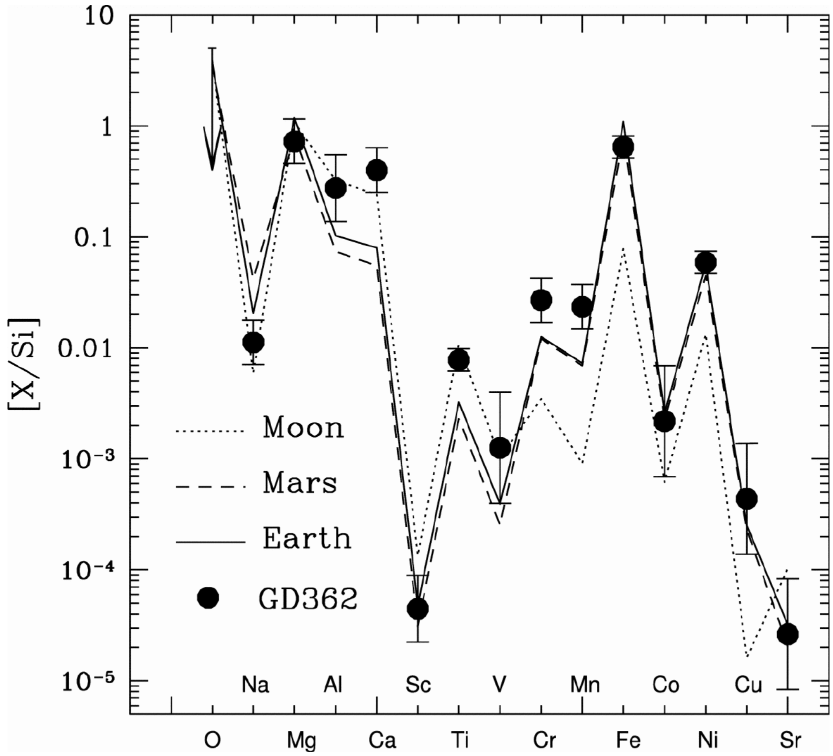

FIGURE 5. Fifteen elements heavier than helium in the highly contaminated photosphere of GD 362 reveal a pattern that is similar to a combination of Earth and Moon compositions. From Zuckerman et al. (2007).

solar terrestrial bodies. But the phenomenon of destroyed and accreted minor planets at white dwarfs needs an evolutionary context, and there are still significant uncertainties in how specific properties arise.

Disk Properties: Frequency and Statistics

After three cycles of *Spitzer* studies of DAZ and DBZ white dwarfs, there were sufficient stars observed to begin robust statistics. Farihi et al. (2009) assembled and analyzed the first 53 metal-rich white dwarfs, finding that the likelihood of a circumstellar dust was strongly linked with the metal accretion rate of the star and its cooling age. The time-averaged metal accretion rate is calculated by multiplying the metal abundance in the star by its convective envelope mass, and dividing by the metal sinking timescale. This essentially assumes a steady-state balance between accretion of heavy elements from an external source and their diffusion below the outer layers (Koester 2009; Koester & Wilken 2006). For the DAZ stars whose diffusion timescales are very short, the assumption of ongoing accretion is physically motivated, while for the DBZ stars the time-averaged accretion rate is simply a valuable diagnostic (Farihi et al. 2009).

Figure 6 plots the inferred metal accretion rates versus cooling age for all polluted white dwarfs observed by *Spitzer* to date, and distinguishes between those stars with

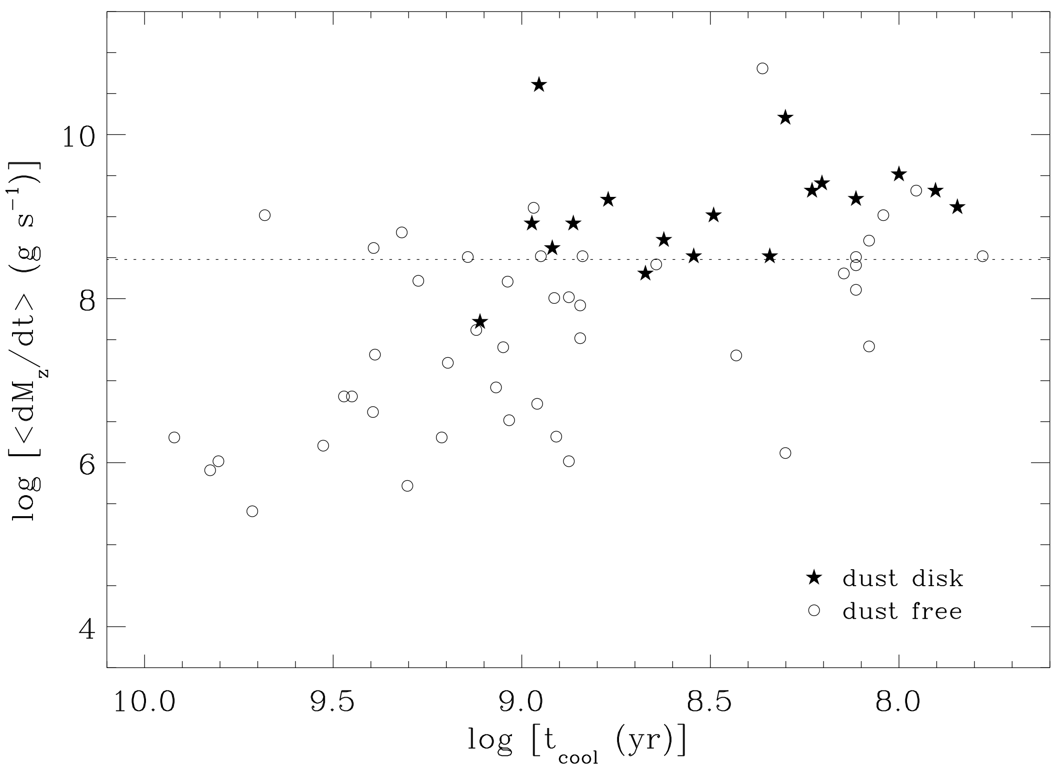

FIGURE 6. Dust disk frequency among all 61 metal-rich white dwarfs observed by *Spitzer* IRAC. Plotted on are the time-averaged metal accretion rate and cooling age for each star. The dotted line corresponds to $3 \times 10^8\,\mathrm{g\,s^{-1}}$. G166-58 is the only star with a disk that is located significantly below this accretion rate benchmark, and with a cooling age beyond 1 Gyr (Farihi et al. 2008b). Adapted from Farihi et al. (2010c).

infrared excess and those without. As can be seen in the plot, for accretion rates above $3 \times 10^8\,\mathrm{g\,s^{-1}}$, there is a greater than 50% chance a white dwarf will have an infrared excess due to dust. This makes physical sense because the greater the ongoing accretion rate, the (presumably) more massive the reservoir that is supplying the metals. This trend is also consistent with the idea that more massive disks should have a sufficiently high surface density to eschew being mostly or totally vaporized via collisions (Jura 2008). In essence, massive disks are tightly packed, with the inter-particle spacing of the same order as the particle size, effectively damping out collisions (Farihi et al. 2008b).

Another observed trend is that dust disk frequency correlates with younger cooling ages. However, this trend contains a bias because metals can only be detected warmer and younger white dwarfs when the pollution is relatively high. Still, there is only a single white dwarf with atmospheric metals and an infrared excess at ages beyond 1 Gyr (Farihi et al. 2010c).

When one views these metal-rich stars statistically, as being drawn from larger samples of white dwarfs in general, the overall result is that between 1% and 3% of all white dwarf with cooling ages less than around 0.5 Gyr have both metal-enriched atmospheres

and circumstellar dust. Such a picture is consistent with the dynamical resettling of a planetary system in the post-main sequence (Debes & Sigurdsson 2002), and the relative dearth of disks at older cooling ages may represent the depletion of large asteroids necessary to create an infrared excess (Farihi et al. 2009). Minimally at the few percent level, white dwarfs with dust represent an underlying population of stellar systems harboring the remnants of terrestrial planets (Farihi et al. 2009), and therefore at least this fraction of A- and F-type stars are likely to build rocky planets.

Narrow Dust Rings or Largely Gaseous Disks

Figure 6 also demonstrates that the majority of observed metal-rich white dwarfs do not exhibit infrared excess detectable by *Spitzer*, including some of the most highly polluted stars. Prior to the launch of *Spitzer* it was suggested that unseen, low-mass stellar and brown dwarf companions could be responsible for the metal pollution seen in some white dwarfs, e.g. via wind capture (Dobbie et al. 2005; Holberg et al. 1997). However, the mid-infrared photometry and spectra of metal-lined white dwarfs rules out the presence of low-mass companions down to $25\,M_{\rm Jup}$ and in some cases to even lower substellar masses (Farihi et al. 2008a; Baraffe et al. 2003). Where found, the detected infrared excesses cannot be reproduced by substellar atmosphere models, while the majority of metal-rich stars simply have no infrared excess where one would be expected if a companion were present (Farihi et al. 2009).

A realistic possibility for those stars with relatively long metal sinking timescales (DBZ and very cool DAZ stars) is a depleted disk. In this case, the extant photospheric metals are the scars of a previous accretion event that took place within a few diffusion timescales (Farihi et al. 2009). In these cases one might expect to see abundances that reflect this fact, as iron sinks most rapidly, while lighter metals such as sodium and magnesium diffuse more slowly (Koester 2009).

However, there are many cases of white dwarfs where metal accretion must be ongoing due to their very short diffusion timescales (Koester & Wilken 2006). For these stars where an infrared excess is not detected, accretion is occurring but not being detected. If collisions within an evolving disk typically grind down solids into particles too small ($2\pi a/\lambda \ll 1$) to emit efficiently at infrared wavelengths, then a largely or totally gaseous disk may result (Farihi et al. 2008b). Furthermore, asteroid destruction within the Roche limit of a white dwarf should occur more frequently for small asteroids as they should be more populous and their low mass implies they will be more readily perturbed into an eccentric orbit. Such multiple impacts on a pre-existing disk will strongly enhance collisions and sputtering and should result in substantial gaseous circumstellar material (Jura 2008).

Another possibility is that many white dwarfs have circumstellar dust from which they are accreting, but the infrared signature of the disk is subtle or undetectable. Figure 7 shows the relatively subtle infrared excesses of two metal-rich white dwarfs observed by *Spitzer*. In each case, the excess is in the $3-5\sigma$ range, whereas a typical dust disk like G29-38 is detected at $15-20\sigma$ (Farihi et al. 2010c). Importantly for the physics involved, narrow rings with radial extents in the range $\Delta r = 0.01-0.1\,R_\odot$ are possible

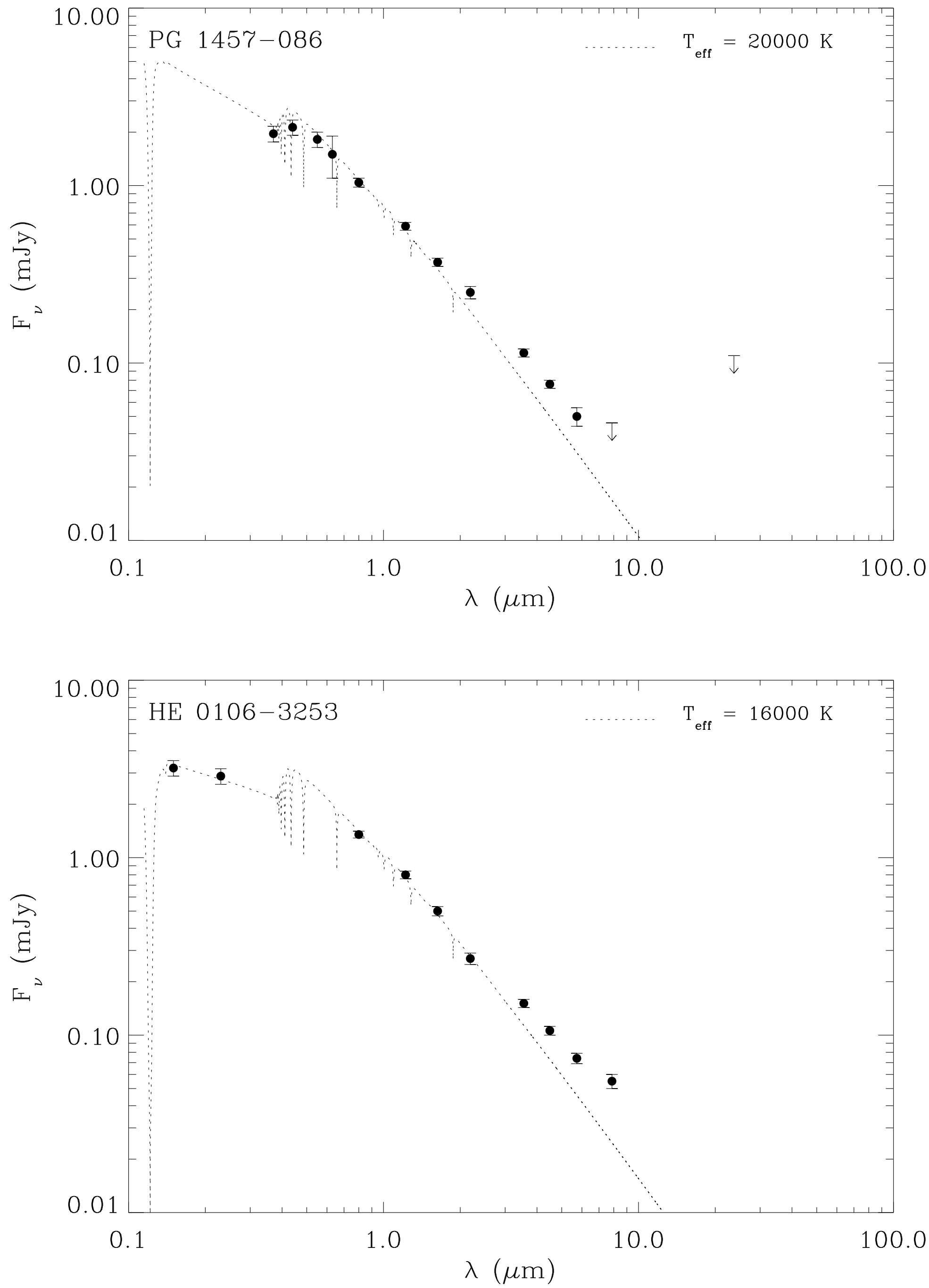

FIGURE 7. The two most subtle infrared excesses detected from narrow, circumstellar dust rings (Farihi et al. 2010c, 2009). Without supporting short wavelength data, the infrared photometry would have been difficult to interpret as an excess with confidence.

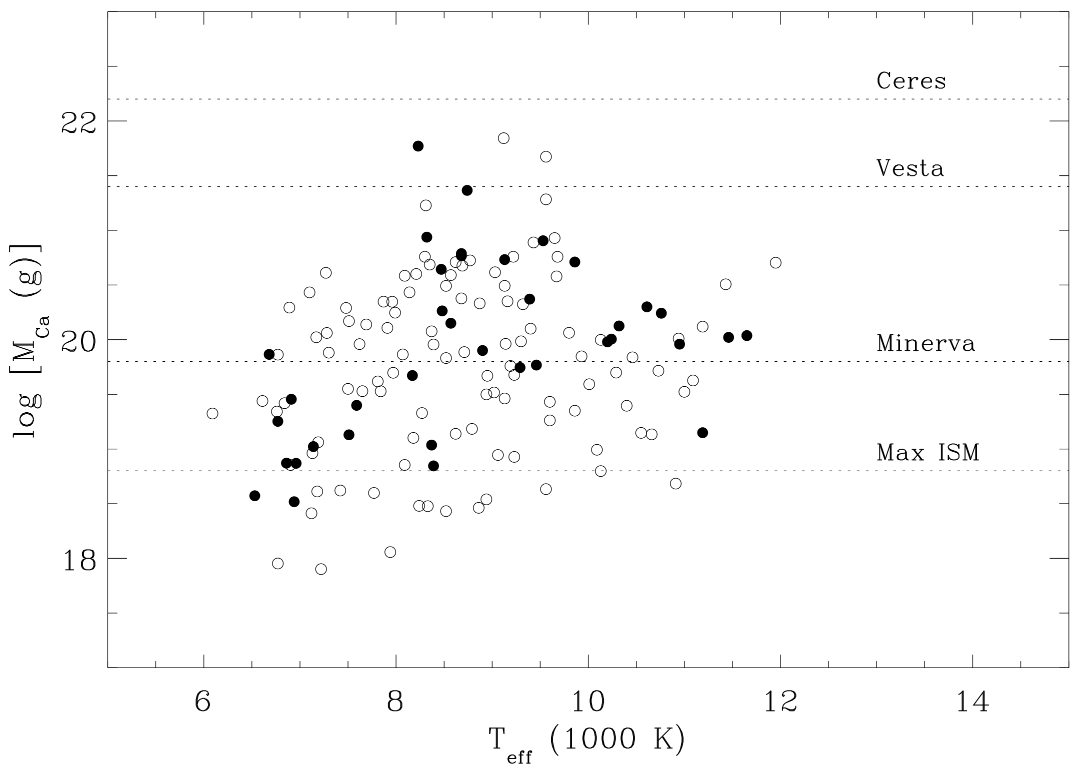

FIGURE 8. Calcium masses in the convective envelopes of 146 DBZ stars from the SDSS. The open and filled circles represent stars with and without trace hydrogen, respectively. The top three dotted lines mark the mass of calcium contained in the two largest Solar System asteroids Ceres and Vesta, and the 150 km diameter asteroid Minerva, assuming calcium is 1.6% by mass as in the bulk Earth (Allègre et al. 1995). The dotted line at the bottom is the maximum mass of calcium that can be accreted over 10^6 yr by a cool white dwarf moving at a velocity of $50\,\mathrm{km\,s^{-1}}$ through an interstellar cloud with a density of $1000\,\mathrm{cm^{-3}}$. Adapted from Farihi et al. (2010a).

but would not necessarily produce an excess unless viewed at a modest inclination angle. Yet dust rings this narrow would still contain sufficient mass to pollute a typical white dwarf for $10^5 - 10^6$ yr at the accretion rates inferred for highly polluted stars (Farihi et al. 2010c).

In summary, those stars with infrared excess and dust may be the result of a single, large asteroid and hence spectroscopy of their polluted atmospheres will yield the *composition of a planetary embryo or fragment*. For those stars without obvious infrared excess, multiple events may have caused the debris to become largely gaseous, and spectroscopy of these stars may reveal the *composition of an ensemble of smaller asteroids*.

The End of the Interstellar Accretion Hypothesis

The accumulated evidence of the past several years strongly supports the idea that white dwarfs with metals are polluted by their immediate circumstellar environments, and not by the interstellar medium. In fact, there is a distinct lack of evidence favoring the interstellar medium.

A recent analysis of nearly 150 metal-polluted (DBZ-type) white dwarfs discovered in the SDSS used several diagnostics to test the feasibility of interstellar accretion for stars generally far more distant than previous studies. No correlation was found between the metal content of the stars and their space velocities, as expected for Bondi-Hoyle type accretion, nor with their distance from the Galactic plane, as expected if the stars are capturing material from within the spiral arms of the Galaxy (Farihi et al. 2010a). Furthermore, many of these stars are located far above the $\pm$ 100 pc thick gas and dust layer of the Galaxy, having spent several to tens of Myr outside the dominant source of interstellar matter. Figure 8 perhaps illustrates best that interstellar accretion simply cannot account for the metal content of these stars. Simply stated, the white dwarfs contain large asteroid-size masses of heavy elements that cannot have been accreted from the ISM by any reasonable physical model (Farihi et al. 2010c).

Thus, interstellar accretion is no longer viable. Specifically, it cannot account for the observed population of metal-enriched white dwarfs. Circumstellar pollution – planetary system remnants – is currently the only plausible and substantiated model.

OUTLOOK IN A NEW PARADIGM

Evidence for Water-Rich Asteroids

The now complete transition to the planetary systems as the standard model for metals in white dwarfs suggests that other models for the origin and evolution of cool white dwarf atmospheres may benefit from reexamination. For example, the hydrogen deficiency of helium atmosphere white dwarfs (both with and without metals) has always been a problem, as accretion from the interstellar medium should quickly convert them to hydrogen-rich atmospheres (Koester 1976). In the planetary system view, trace hydrogen can be delivered to the white dwarf in water-rich asteroids.

The main asteroid belt in the Solar System is at least 6% water by mass (due to the 25% water content of Ceres; Thomas et al. 2005), and it is reasonable to suppose that extrasolar asteroids will contain water. While surface and near-surface water ice and volatiles will be evaporated due to heating during the asymptotic giant evolution of the white dwarf progenitor, interior water should survive in moderate to large size asteroids (Jura & Xu 2010). If one examines the relative fractions of cool, helium-rich white dwarfs with 1) trace metals, 2) trace hydrogen, or 3) both, then the last category should occur with the lowest frequency if the origin of the trace metals and the trace hydrogen are independent. In contrast, trace to these expectations, trace hydrogen is found more often in those stars with trace metals, indicating the possibility of water within the parent body that delivered the metals (Farihi et al. 2010a).

There are a few examples of white dwarfs where the accretion of water-rich planetary

material seems likely. Both GD 362 and GD 16 have circumstellar disks, photospheric metals, and rather high trace hydrogen abundances compared to other stars of the same effective temperature (Jura et al. 2009b). A dedicated search for atmospheric oxygen at these two stars is sure to be revealing. The white dwarfs GD 378 and GD 61 both have photospheric metals and oxygen detected in the ultraviolet, where the oxygen abundance is in excess of that expected if all the metals were contained in oxides (Jura & Xu 2010). Because oxygen sinks more slowly than elements such as silicon, magnesium, and iron (Koester 2009), the apparent overabundance of oxygen may be superficial. If accretion can be shown to be ongoing in either of these systems, it would be strong evidence that these white dwarfs accreted a rocky parent body rich in water.

Terrestrial Planets at Intermediate Mass Stars

White dwarfs are the evolutionary end point for the vast majority of all stars in the Milky Way. Owing to the shape of the initial mass function and the finite age of the Galaxy, the currently observed disk population is primarily descended from main-sequence A- and F-type stars with masses in the range $1.2-3.0\,M_{\odot}$. The statistics for tidally disrupted asteroids at white dwarfs can be used as a strict lower limit for the frequency of terrestrial planets at their main-sequence progenitors. In this view, A- and F-type stars build terrestrial planets *at least* a few percent of the time, and in some cases there is evidence for water-rich building blocks. If one attributes all metal-polluted white dwarfs to rocky debris, then the fraction of terrestrial planetary systems that survive post-main sequence evolution (at least in part) is as high as 20% to 30% (Zuckerman et al. 2010, 2003). Hence, the rocky planetary system remnants being witnessed at white dwarfs indicates that terrestrial planets are a frequent by-product of intermediate-mass star formation.

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